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(71) Applicant: THE UNIVERSITY OF SUSSEX [GB/GB]; Sussex House, Falmer, Brighton Sussex BN1 9RH (GB).

(72) Inventors: WATERFIELD, James; Pevensey II, University of Sussex, Brighton Sussex BN1 9RQ (GB). SINCLAIR, James; Albert Einstein Centre for Fundamental Physics, Laboratory for High Energy Physics, University of Bern, Sidlerstrasse 5, 3012 Bern (CH). PEETERS, Simon; Pevensey II, University of Sussex, Brighton Sussex BN1 9RQ (GB). WHITE, Richard; Pevensey II, University of Sussex, Brighton Sussex BN1 9RQ (GB).

(74) Agent: DEHNS; PARRY, Thomas, St. Bride's House, 10 Salisbury Square, London Greater London EC4Y 8JD (GB).

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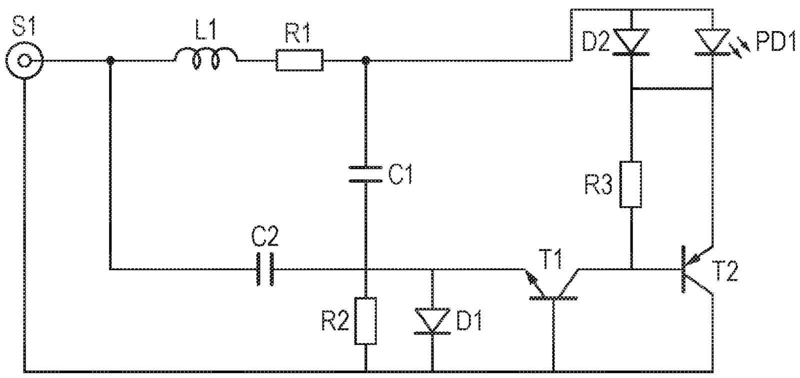
(54) Title: LIGHT PULSE GENERATING CIRCUITS AND SYSTEMS

Fig. 2



(57) Abstract: A light pulse generating circuit is described for generating light pulses from a diode light source such as an LED or laser diode. The light pulse generating circuit comprises a charge storage device and a trigger circuit for triggering a discharge of the charge storage device across the diode light source to generate a light pulse. The light pulse generating circuit comprises a differentiator circuit for differentiating an input signal to produce a differentiated signal, which is provided as an input to the trigger circuit. A first diode is arranged relative to the differentiator circuit in order to substantially prevent the propagation of one of a positive pulse and a negative pulse generated by differentiating the input signal so that a light pulse having a single peak is generated. Also described are methods of using the same, and systems comprising a plurality of light pulse generating circuits arranged in sequence.

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LIGHT PULSE GENERATING CIRCUITS AND SYSTEMS

The present invention relates generally to circuits and systems for generating light pulses.

BACKGROUND

There are various applications requiring faster pulsing of diode light sources such as light-emitting diodes (LEDs) and laser diodes.

One example application is for the calibration of fast optical detectors for instance for use in particle detectors such as neutrino or dark matter detectors for particle physics experiments. These experiments typically comprise a large number of detectors that each need to be calibrated so that a plurality of light sources are required. Both laser diodes and LEDs may be suitable for use as timing calibration sources, and both have previously been used in existing systems. For the purposes of any timing calibration system it is important to keep the time profile of the light pulse as short as practical (for instance, sub-nanosecond pulses), ideally of the same order as the lower limit on the resolution of whatever is being calibrated, whilst also ensuring that the intensity of the light pulse is high enough for the photo detectors. Naturally, it is also important, especially where large numbers of detectors are involved, to keep the size and cost of the calibration sources as low as possible.

Another example application would be for time-resolved fluorescence or photoluminescence analyses such as single photon counting techniques where the temporal profile of the radiation emitted from a material following excitation of the material by a light pulse, typically provided using a laser diode source, is recorded. Typically, only a single light source may be required for these analyses. Again, it is important to keep the light pulse as short as practical.

Other exemplary applications requiring relatively fast light pulses include biochemical analysis, detection of fluorescent materials, optoelectronic device testing, Fourier transform infrared spectroscopy, photo-acoustic microscopy, Raman spectroscopy, laser ionisation sources, gating for medical imaging and radiation therapy, flow cytometry and high speed photography.

There are also various approaches and light pulse generator systems for generating such pulses. However, many of these systems are difficult or expensive to reproduce, often involving relatively complicated or bulky driver circuits.

One existing light pulse generator system that overcomes these problems to some extent is based on the so-called "Kapustinsky circuit", illustrated in Figure 1. The original Kapustinsky circuit was developed by Kapustinsky *et al.* in the 1980's for use in calibration of scintillation detectors and is described in the Letter to the Editor: "A Fast Timing Light Pulser For Scintillation Detectors" by J.S. Kapustinsky *et al.* in Nuclear Instruments and Methods in Physics Research A241 (1985) 612-613. In the original Kapustinsky circuit a capacitor discharge across an LED light source is controlled using a complementary transistor pair regenerative switch.

Although the Kapustinsky circuit has promising timing characteristics, and the ability to provide relatively high amounts of current to the LED light source, whilst utilising relatively compact and inexpensive components, a number of problems remain with the Kapustinsky circuit.

Existing light pulse generator systems are also typically unsuitable for *in situ* installation in harsh environments, such as where a detector may be located. Some existing approaches thus require extensive light-guiding cabling (of tens of meters) in order to transmit the light pulses to the desired region and the light pulses may undesirably spread and broaden during this transmission.

It is therefore desired to provide improved circuits for generating light pulses and improved light pulse generator systems.

SUMMARY

Generally, according to the present invention, there is provided a light pulse generating circuit comprising: an input for receiving an input signal; a diode light source; a charge storage device; a trigger circuit for triggering a discharge of said charge storage device across said diode light source to generate a light pulse; and a differentiator circuit for differentiating said input signal to produce a differentiated signal, wherein the differentiated signal is provided as an input to said trigger circuit to trigger said discharge, wherein a first diode is arranged relative to the differentiator circuit so that when a pulse input signal is provided to the input such that the differentiator circuit differentiates the pulse input signal to produce a differentiated signal comprising a positive pulse and a negative pulse, the first diode substantially prevents the propagation of one of said positive pulse and said negative pulse so that only the other of said positive pulse and said negative pulse is provided as an input to said trigger circuit to trigger the discharge so that a light pulse having a single peak is generated.

The light pulse generating circuit thus comprises a light source and a driver circuit for controlling the light source to generate a light pulse. According to embodiments of the present invention, the driver circuit includes the charge storage device, the differentiator circuit and the trigger circuit and drives the light source in response to receiving an input signal via the input of the light pulse generating circuit. The driver circuit, and hence the generation of light pulses, may thus be controlled or programmed using an external processor and/or power supply connected to the input.

It will be appreciated that the light pulse generating circuits according to embodiments of the present invention use a differentiated input signal to trigger the discharge of a charge storage device across a diode light source to generate a light pulse. That is, the light pulse generating circuits described herein are “edge triggered”. It will be understood however that the differentiated signal need not be provided directly to the trigger circuit and that, in embodiments, various processing steps may be performed on the differentiated signal between the differentiator circuit and the trigger circuit. Similarly, various processing steps may be performed between the input and the differentiator circuit. However, it will generally be understood that the generation of light pulses is triggered in response to the input signal being provided to the circuit, and in particular in response to the differentiated input signal being provided to the trigger circuit. In this respect, it will be appreciated that the circuits described herein share some similarities with the Kapustinsky circuit illustrated in Figure 1.

However, the Applicants have recognised that existing light pulse generating circuits based on the Kapustinsky circuit, such as that illustrated in Figure 1, may generate a “double” optical pulse output, especially when the circuit is used to drive current generation diode light sources (which may be faster than those used in the original Kapustinsky circuit). For example, when a pulse input signal (such as a square or rectangular pulse) is provided to the circuit illustrated in Figure 1, the differentiator circuit will act to differentiate the leading and trailing edges of the pulse such that both a positive pulse, from differentiating the rising edge, and a negative pulse, from differentiating the falling edge, are generated. Both of these pulses can potentially trigger the discharge of the charge storage device and so, especially for relatively fast LEDs or laser diode light sources, the generated light pulse may contain a double peak. This may effectively result in a broadening of the light pulse.

By contrast, according to the present invention, a (the first) diode is arranged so as to remove one of the pulses (i.e. either the positive or negative pulse) from the differentiated signal so that the generated light pulse(s) contain only a single peak. The light pulses generated according to embodiments of the present invention may thus be shorter or sharper than those that would be generated using previous circuits like that shown in Figure 1. Particularly, a diode is arranged to remove the undesirable double pulsing effect that may otherwise be present with existing driver circuits based on the original Kapustinsky circuit. In embodiments, the circuits described herein may be able to provide faster light pulses than the original Kapustinsky circuit. Particularly, the circuits described herein may be substantially optimised for use with faster diode light sources. Furthermore, it will be appreciated that the addition of this first diode does not add significant bulk or expense to the circuit. Thus, a significant improvement in performance may be achieved without sacrificing any of the benefits provided by the original Kapustinsky circuit compared to other approaches for generating light pulses in terms of size and cost.

The input signal may generally be provided in the form of a pulse. It will be understood that a “pulse” is generally a signal that changes from a baseline value to a higher or lower value, and then returns to the baseline value. That is, a pulse may be a characterised by a rising edge and a falling edge. Although for most applications the input signal typically will comprise a square or rectangular pulse, it will be appreciated that the input signal may be provided in various suitable forms, such as various other pulse shapes, or in the form of a wave or pulse train, and that the circuits described herein may in general act to generate light pulses based on various suitable input signals. For instance, and generally, the differentiator circuit may differentiate the input signal to produce a differentiated signal having a first component (or set of components) of positive polarity and a second component (or set of components) of negative polarity and the (first) diode may thus be arranged relative to the differentiator circuit so as to substantially prevent the propagation of either the first or the second component(s) of the differentiated signal so that only the other of the first or second component(s) (or only at least some of the other first or second component(s)) is used to trigger said discharge. Generally therefore, the effect of the (first) diode may be to only allow the components of the differentiated signal having a certain polarity (i.e. either positive or negative) to be transmitted towards the trigger circuit and used to trigger the discharge of the charge storage device.

The (first) diode is generally located next to the output of the differentiator circuit so that the differentiated signal passes to the trigger circuit via the first diode. It will be appreciated however that various circuit designs may be realised including a first diode arranged in a suitable manner relative to the differentiator and trigger circuits.

Depending on the arrangement of the circuit (and the polarity of the input signal), the (first) diode may be arranged so as to prevent either of the positive or negative pulses from propagating.

In preferred embodiments, the input signal provided to the circuit has a positive polarity. That is, the components of the circuit are arranged to generate light pulses having single peaks in response to receiving a positive input signal from or via the input. For example, where the input signal comprises a positive rectangular pulse such that the differentiated signal comprises a leading negative pulse and a trailing positive pulse, the first diode may be arranged to prevent the propagation of the positive pulse, so that only the negative pulse is used to activate the trigger circuit. It will be appreciated that whether the negative or positive pulse is used to activate the trigger circuit will generally depend on the arrangement of the trigger circuit and the diodes, and may thus be selected as desired by appropriately configuring the circuit. That is, depending on the arrangement of the circuit, either of the negative or positive pulses may be used to activate the trigger circuit (and the double pulse feature will be avoided so long as one of them is removed).

The light pulse generating circuit may generally comprise one or more inputs for receiving a respective one or more input signals. The input signal(s) may generally comprise a power signal for charging the charge storage device and a trigger signal that is passed to the differentiator and trigger circuits and used to trigger the discharge of the charge storage device.

One drawback of the original Kapustinsky circuit is that a negative power supply is used which may be incompatible with various other devices to which it is desired to interface the circuit. For example, the circuits described herein may generally be coupled to a computer system or processor for controlling the operation of the light generating circuit. However, standard modern electronic control devices typically have power supplies that work at positive voltages, for instance in the range + 0 to 30 V, or + 5 to 30 V. An example of this would be a standard computer or laptop with a USB or Ethernet connection including a + 5 V power output. Accordingly, arranging the circuit to operate with positive input and/or power signals may facilitate the use of the circuit with existing, standard control components such as processors and/or power supplies. This may in turn facilitate the realisation of a relatively simple and inexpensive light pulse generator system. Preferably, therefore, the light pulse generating circuit is arranged for use with a positive power signal, so that a positive power signal may be used to charge the charge storage device. Preferably, the power signal used to charge the charge storage device and the input (trigger) signal that is differentiated and used to trigger the discharge of the charge storage device are both positive.

Accordingly, from another aspect, there is provided a circuit for generating light pulses comprising: one or more inputs for receiving a power signal and a trigger signal, wherein said power signal and said trigger signal are each positive; a diode light source; a charge storage device which is charged using said power signal; a trigger circuit for triggering a discharge of said charge storage device across said diode light source to generate a light pulse; and a differentiator circuit for differentiating said trigger signal to produce a differentiated signal, wherein the differentiated signal is provided as an input to the trigger circuit to trigger said discharge, wherein a first diode is arranged relative to the differentiator circuit so that when a positive pulse input signal is provided as the trigger input signal such that the differentiator circuit differentiates the positive pulse input signal to produce a differentiated signal comprising a positive pulse and a negative pulse, the first diode substantially prevents the propagation of one of said positive pulse and said negative pulse so that only the other of said positive pulse and said negative pulse is provided as an input to the trigger circuit to trigger the discharge so that a light pulse having a single peak is generated.

The form and length of the input signal may be selected appropriately depending on the desired light pulse output. For instance, in some embodiments, typical input signals may comprise rectangular pulses having lengths of around 1 microsecond. Shorter pulses may be used for higher speed applications. For example, at 10 MHz, pulse widths of around 50 nanoseconds may be suitable.

Preferably, the same input signal that is ultimately used to trigger the discharge of the charge storage device may also be used to charge the charge storage device. That is, the circuits described herein may have a common (or single) input for receiving both the power signal(s) used to charge the charge storage device and the trigger signal(s) used to trigger the generation of light pulses. Thus, the input signal may comprise a power signal component and a trigger signal component. For example, in embodiments, the input signal may comprise a DC voltage and a trigger signal such as a pulse, or preferably a rectangular pulse. The trigger signal may thus be superimposed on the DC power supply. Thus, the power signal component (e.g. DC voltage) of the input signal may be used to charge the charge storage device whereas the trigger signal component (e.g. rectangular pulse) of the signal may be passed to the differentiator circuit and the differentiated trigger component used to trigger the discharge of the charge storage device. In embodiments, an inductor or other reactive component may be provided for splitting or decoupling the power and trigger signal components of the signal.

Accordingly, from another aspect, there is provided a circuit for generating light pulses comprising: an input for receiving an input signal; a diode light source; a charge storage device which is charged using (a first component of) the input signal; a trigger circuit for triggering a discharge of said charge storage device across said diode light source to generate a light pulse; and a differentiator circuit for differentiating (a second component of) said input signal to produce a differentiated signal, wherein the differentiated signal is provided as an input to the trigger circuit to trigger said discharge, wherein a first diode is arranged relative to the differentiator circuit so that when a pulse input signal is provided to the input such that the differentiator circuit differentiates the pulse input signal to produce a differentiated signal comprising a positive pulse and a negative pulse, the first diode substantially prevents the propagation of one of said positive pulse and said negative pulse so that only the other of said positive pulse and said negative pulse is provided as an input to said trigger circuit to trigger the discharge so that a light pulse having a single peak is generated.

Other embodiments are contemplated wherein the circuit may be provided with separate inputs for the trigger signal and the power signal and this may help to reduce the effect of noise on the trigger signal. In these embodiments, the circuit may thus comprise a first input for receiving a power signal and a second input for receiving a trigger signal, wherein the power signal is used to charge the charge storage device and wherein the trigger signal is differentiated and the differentiated trigger signal is provided as an input to the trigger circuit to trigger the discharge. However, for the circuits and applications described herein it has been found that this may not be necessary and that it may be more advantageous to provide a common (or single) input to facilitate miniaturisation and control of the circuit.

In general, the input to the circuit may take various suitable forms depending on how the circuit is desired to be controlled and/or interfaced with external components. Indeed, an advantage of the circuits described herein is that they may be incorporated into a relatively compact system and may be controlled using relatively simple commercially available controllers. The input may e.g. comprise a co-axial cable. The input may comprise an Ethernet or USB connector for connecting the circuit to an external computer, processor and/or electronic power supply. The circuit may generally be provided within a single housing, or on a single PCB, with the input provided in the housing or PCB allowing the circuit to be simply plugged in to an external computer, processor and/or electronic power supply. The circuit and/or housing may be relatively compact. Thus, an integrated system comprising a programmable driver circuit packaged together with a light source may be provided within a common housing. For example, the total volume of the circuit and/or the housing may be around 10 cm^3 or less.

The diode light source may comprise various suitable diode or solid-state light sources. For instance, the diode light source may comprise either an LED or laser diode light source. In general, LED light sources may be more robust and/or cheaper than laser diode sources, whereas laser diodes may provide some higher performance (at least in some respects). However, recent developments in LED manufacture have led to LEDs that exhibit comparable brightness, speed and efficiency with laser diode light sources. In particular, it has been found that LED light sources having relatively low resistances may be suitably used within the circuits described herein. For instance, LED light sources having resistances of less than 20 Ω, such as less than 15 Ω, or less than 10 Ω may be particularly suitable. It will be appreciated that these resistances are relatively low compared to traditional LEDs used in previous light pulse generator systems such as the original Kapustinsky circuit, which may have typical resistances ranging from about 40 to 100 Ω. The present invention recognises that the use of lower resistance LEDs in turn allows various improvements to be made to the original Kapustinsky circuit to improve the light pulse generating performance.

For instance, in the original Kapustinsky circuit shown in Figure 1, an inductor is connected in parallel with the LED light source. This inductor acts to generate charge carriers in opposition to the LED, which has the effect of reverse biasing the LED and facilitating removal of charge carriers from the LED, thus reducing the pulse time. However, the Applicants have recognised that this inductor may significantly reduce the amplitude of the generated light pulses, and hence require larger and/or higher rated power sources in order to generate brighter light pulses.

With the circuits described herein, it has been found that similar, or even sharper, pulse widths can be achieved without the inductor. Particularly, where the diode light source has a relatively low resistance (e.g., less than about 20 Ω, or less than about 15 Ω or 10 Ω), it has been found that the addition of an inductor in parallel with the diode light source is not necessary as the lower resistance allows more current to be passed through the diode light source which may help to produce sharper light pulses. Advantageously, according to the embodiments described herein, there may be no inductor connected in parallel with the diode light source. This may allow for more intense light pulses to be generated without requiring larger power supplies. Alternatively, this may allow smaller power supplies to be used. Either way, this may facilitate incorporation of the circuit within a relatively compact system, and allows the circuit to be readily interfaced with simple control or processing electronics.

In embodiments, regardless of whether or not an inductor is provided, a second diode may be connected in parallel with the diode light source. The second diode may be used for current shaping purposes to help shape or control the generated light pulse. In particular, the second diode may be arranged to control how much current is passed through the diode light source in order to control the pulse width. In embodiments, only the second diode is arranged in parallel with the diode light source. In other embodiments, no second diode and no inductor are provided in parallel with the diode light source.

Thus, from a further aspect, there is provided a circuit for generating light pulses comprising: an input for receiving an input signal; a diode light source, wherein no inductor is connected in parallel with the diode light source; a charge storage device; a trigger circuit for triggering a discharge of said charge storage device across said diode light source to generate a light pulse; and a differentiator circuit for differentiating said input signal to produce a differentiated signal, wherein the differentiated signal is provided as an input to said trigger circuit to trigger said discharge, wherein a first diode is arranged relative to the differentiator circuit so that when a pulse input signal is provided to the input such that the differentiator circuit differentiates the pulse input signal to produce a differentiated signal comprising a positive pulse and a negative pulse, the first diode substantially prevents the propagation of one of said positive pulse and said negative pulse so that only the other of said positive pulse and said negative pulse is provided as an input to said trigger circuit to trigger the discharge so that a light pulse having a single peak is generated.

However, embodiments are also contemplated wherein an inductor may be provided, and particularly wherein an inductor and a second diode may both be provided, in parallel with the diode light source. This arrangement may help further reduce the pulse width.

The diode light source may operate at various wavelengths depending on the desired application. For example, the diode light source may generate light pulses with a center wavelength within the range between about 250 and 700 nm. However, it will be appreciated that the circuits described herein are not limited in this respect and may be appropriately modified to work at (i.e. to work with diode light sources that operate at) various other suitable wavelengths.

The charge storage device may generally comprise one or more capacitors. The capacitance of the charge storage device ultimately limits the amount of current that is discharged through the diode light source and the capacitance may thus be selected appropriately depending on the desired intensity for the generated light pulses. Depending on the desired application, a typical capacitance may be around 100 pF.

The charge storage device may generally be charged using a power signal provided as input to the circuit. As discussed above, the power signal may comprise a component of the same input signal that is used to trigger the discharge of the charge storage device, so that the power signal and trigger signal are both provided as part of the input signal through a common input or as a combined input signal. One or more resistors may be incorporated within the circuit in order to control the rate of charging the charge storage device. In general, the lower the resistance, the faster the charge storage device may be charged. For instance, a resistor having a value within the range of about 1 kΩ to about 100 kΩ may be used in order to vary the rate at which the charge storage device is charged. The rate at which the charge storage device (e.g. capacitor) can be charged may determine the maximum repetition rate of the circuit (i.e. the rate at which light pulses can be generated). For example, a 1 kΩ resistor may allow maximum repetition rates of 10 MHz or above, such as between about 10 and 100 MHz.

Various suitable trigger circuits may be used with the circuits described herein. In some embodiments, the trigger circuit may comprise a pair of transistors. Particularly, the trigger circuit may comprise a complementary transistor pair regenerative switch of the type used in the original Kapustinsky circuit.

Similarly, various suitable differentiator circuits may be used with the circuits described herein. In embodiments, the differentiator circuit may be a passive differentiator circuit comprising a resistor-capacitor pair.

It will be appreciated that various other components may be included within the circuits described herein, for instance, for filtering or suppressing noise, particularly between the input and the trigger circuit.

The circuit may be connected, in use, to one or more processors and/or power supplies for providing the input signal(s) for controlling the generation of the light pulse(s). The input may thus comprise a suitable connection for connecting the circuit to an external computer, processor or power supply. For instance, the input may comprise a USB or Ethernet connection to facilitate connecting the circuit to a standard laptop computer or mobile device. In embodiments, the connection may be wireless, e.g., using a Bluetooth® or other suitable wireless connection protocol.

From another aspect, there is provided a light pulse generator system comprising a light pulse generating circuit substantially as described herein in relation to any of the aspects or embodiments of the invention and one or more processors and/or power supplies for providing one or more input signal(s) to the light pulse generating circuit.

A plurality of light pulse generating circuits may be combined into a single system or apparatus. For instance, a plurality of light pulse generating circuits may be arranged so that the plurality of light pulse generating circuits share a common central control unit, or are connected to a common processor and/or power supply. For example, where the system is used as a timing calibration within a detector system, using a common control unit or processor may allow the calibration to be performed for multiple detectors of the detector system.

From a further aspect, there is provided a light pulse generator system comprising a plurality of light pulse generating circuits substantially of the types described herein in relation to any of the aspects or embodiments of the invention, wherein the plurality of light pulse generating circuits are distributed along a (single) cable; and a central control unit, wherein said central control unit is connected to said cable and arranged to transmit control signals along said cable for addressing each of said plurality of light pulse generating circuits.

According to this aspect, each of the light pulse generating circuits may be installed at a different location, e.g., distributed throughout the detector, to minimise the distance that the generated light pulses have to travel. By contrast, in existing timing calibration systems each of the light pulse generating circuits are typically mounted outside of the detector, and the light pulses are transmitted to the desired locations via optical fibre cabling. This transmission may result in an undesirable dispersion and broadening of the light pulses which may be avoided according to distributing the pulse generating circuits along a common cable. The relatively compact and robust nature of the light pulse generating circuits described herein may facilitate their installation *in situ* within the detector, even in relatively harsh operating conditions.

The plurality of light pulse generating circuits may thus be arranged in sequence along a common cable such that each of the light pulse generating circuits may be individually, or independently, addressed. That is, signals and/or information may be sent along the common cable to (or from) each of the plurality of light pulse generating circuits independently.

Each of light pulse generating circuits may be connected to and in communication with the central control unit using a common cable. Thus, control signals may be sent from the central control unit to each of the light pulse generating circuits along the common cable. Each of said plurality of circuits may be individually addressable by said central control unit. Signals may also be sent back from the light pulse generating circuits to the central control unit along the same (or alternatively a further) cable. For instance, in embodiments, each of said plurality of circuits may comprise feedback circuitry arranged to send a signal along said common cable to said central control unit to indicate the generation of a light pulse. Because the circuits may be distributed along the system, and may thus be activated at different times, it may be important, especially for timing calibration systems, to know when the light pulses were generated and/or to be able to account for the delay(s) between sending a signal from the central control unit to a particular light pulse generating circuit and a light pulse being generated at that circuit. For instance, this may help improve the accuracy of the calibration and/or help in diagnosing or identifying faults within the system. In embodiments, the system may be arranged so that the feedback signal indicating the triggering of a particular light pulse generating circuit arrives at the central control unit simultaneously with the generation of a light pulse. For instance, each of the plurality of circuits may further comprise a delay module for introducing a selected, e.g. pre-configured or programmed delay into the light pulse generating circuit in order to delay the generation of a light pulse by a time that substantially matches the time taken for the feedback signal to reach the central control unit. The delay module may be configured or programmed during or prior to installation, or may be configured or programmed *in situ* from the central control unit.

From a further aspect, there is thus provided a method of using the system according to this aspect, or any embodiments of this aspect, comprising installing each of the plurality of light pulse generating circuits at a respective position where it is desired to generate a light pulse; and transmitting a control signal from a central control unit to one or more of said plurality of light pulse generating circuits in order to generate a light pulse at the respective positions of the one or more light pulse generating circuits.

In general, the light pulse generating circuits and systems described herein may be used by providing an input signal to the light pulse generating circuit(s); and using the light pulse generating circuit(s) to generate a light pulse. The input signal may comprise a pulse, such as a square or rectangular pulse. Optionally, the input signal may comprise a positive pulse.

From a further aspect, there is thus provided a method of using a light pulse generating circuit, or a system, according to any of the embodiments or aspects described herein comprising: providing an input signal to the light pulse generating circuit(s); and using the light pulse generating circuit(s) to generate a light pulse. The input signal may comprise a pulse, such as a square or rectangular pulse, and optionally may comprise a positive rectangular pulse. The method may further comprise providing a positive power signal to the light pulse generating circuit(s) for charging the respective charge storage device(s), optionally wherein said input signal is superimposed on the positive power signal.

The light pulse generating circuits and systems described herein may be used to generate light pulses having a wide range of properties through appropriate selection of the various circuit components. For example, the light pulses generated according to the techniques described herein may generally have pulse widths of the order of nanoseconds, and may preferably generate sub-nanosecond pulses. The pulses may be generated at a range of frequencies ranging from a single shot to tens of MHz. The intensity of the light pulses may be varied by changing the size of the charge storage device and/or the amount of power input into the circuit. Generally, pulses may be generated having intensities ranging from about 100 to about 1000000 photons per pulse, although it will be appreciated that the intensity may be increased by many orders of magnitude by increasing the generated pulse width.

It will be appreciated that an advantage of the circuits described herein is that they are relatively simple, and may utilise existing commercially available components. This may allow the circuits to be readily tailored in order to provide a desired specification for a particular application.

BRIEF DESCRIPTION OF THE DRAWINGS

Various embodiments will now be described, by way of example only, and with reference to the accompanying drawings in which:

Figure 1 shows the circuitry for a known light pulse generating system (the “Kapustinsky circuit”);

Figure 2 shows a circuit for driving a pulsed diode light source according to a preferred embodiment of the present invention;

Figure 3 illustrates how the form of the input trigger signal changes at various positions within the circuit of Figure 2;

Figure 4 shows schematically the concept of arranging a plurality of driver circuits in sequence; and

Figure 5 illustrates a further example of the concept shown in Figure 4.

DETAILED DESCRIPTION

The original Kapustinsky circuit is illustrated in Figure 1. In the circuit shown in Figure 1, an external trigger signal is sent to the driver board circuitry on a co-axial cable the trigger signal comprising a negative pulse (– 1.5 V, with a minimum width of 150 ns) that rides on a variable negative DC bias level (– 0-24 V). The DC component of the trigger signal charges a 100 pF storage capacitor. The falling edge of the input signal is differentiated by a resistor-capacitor combination, and the differentiated input pulse switches on the complementary pair regenerative switch consisting of the two transistors BFR93A and BFT92. The subsequent circuit path to ground provides a low impedance path to ground across the LED light source for the 100 pF storage capacitor to discharge. In the original Kapustinsky circuit, described above, a 2.2 mm diameter green LED with a peak emission wavelength of 565 nm was used as the light source.

As shown in Figure 1, an inductor (100 nH) is provided in the circuit connected in parallel with the LED. This inductor develops charge in opposition to the discharging capacitor, hence reverse biasing the LED and sweeping its trapped charge carriers away from the depletion layer. This action reduces the fall time or decay constant τ of the light pulse, which follows the time dependence ~ $e^{-t/\tau}$, hence producing a sharper pulse (as compared with no inductor in the circuit). With no inductor in the circuit, the decay constant was measured to be about 100 ns. The addition of the 100 nH inductor was found to shorten this to approximately 12.5 ns.

Figure 2 shows a pulse generating circuit for a diode light source PD1 according to embodiments of the present invention. The circuit shown in Figure 2 shares some similarities with, but represents an improved modification of, the original Kapustinsky circuit.

The diode light source PD1 shown in Figure 2 comprises an LED. However, it will be appreciated that the diode light source PD1 in general may equally comprise various other suitable solid-state light sources such as laser diodes, and that the advantages provided by the embodiments described herein are not necessarily limited to driver circuits for LED light sources.

In preferred embodiments the performance of the circuit is improved by using relatively low resistance diode light sources. However, in turn, the circuit is substantially optimised for use with such diode light sources. For instance, where an LED is used, the LED may have a resistance of around 10 Ω or less in the near linear region of forward current against forward voltage above the LED threshold voltage. By contrast, the resistance of typical LEDs used in conventional light pulse generating systems, such as those used in the original Kapustinsky circuit shown in Figure 1 would be much higher, for example, between about 40 and 100 Ω. Suitable low resistance LEDs having a range of peak wavelengths from ultraviolet to infrared may, for instance, be obtained from Brite LED of Florida.

Again, in the Figure 2 circuit, a single input signal S1 is provided to the circuit via a co-axial cable wherein the input signal comprises a DC component (the power component) and a trigger pulse (the trigger component). The DC component ultimately determines the intensity or amplitude of the light pulse whereas the trigger pulse controls the timing of the generation of the light pulse. An inductor L1 is provided in the circuit that acts to separate the trigger pulse component from the DC component.

In some alternative embodiments the trigger pulse input and the DC input may be provided via separate input lines, and this may help reduce noise on the input line. However, preferably, a single input line is used, as this may help reduce the size and complexity of the circuit, and facilitate interfacing the circuit with external processors and/or power supplies.

It will be appreciated that the circuit shown in Figure 2 is inverted relative to that shown in Figure 1. That is, the Figure 2 circuit works with a positive power supply for charging the charge storage device and a positive input signal for triggering the discharge, rather than negative input signals as used in the original Kapustinsky circuit. The input signal may thus comprise a positive pulse superimposed on a positive DC bias level. It has been found that inverting the circuit to work with positive input signals and/or power supplies may advantageously allow the circuit to be interfaced with more standard processors and/or power supplies, thus simplifying the system control requirements and facilitating providing a relatively inexpensive and compact light pulse generator system. For instance, the DC bias level may e.g., be variable between + 0 and 30 V, or fixed e.g. at about + 5 V, to accommodate standard power supplies. Because the circuit is arranged for use with a positive input signal, the circuit may be readily connected or interfaced to standard power supplies and/or processors. For instance, the circuit may be provided with a USB or Ethernet connection allowing the circuit to be simply connected to a standard computer such as a laptop or a Raspberry Pi® for controlling the operation or programming the circuit. This compatibility with existing devices facilitates the realisation of a robust and inexpensive light pulse generator system relying on readily available components.

The DC component of the input signal is used to charge a charge storage device in the form of a capacitor C1. The size of the capacitor C1 may generally be chosen as appropriate to control the amount of charge stored, and hence the discharge through diode light source PD1 and the intensity of the light pulse. For typical optical detector calibration applications, a capacitance of around 100 pF has been found to be appropriate, however it will be understood that various sizes of capacitor or arrays of capacitors may suitably be used. The rate of charging the capacitor C1 may be controlled in part by appropriately selecting or adjusting the value of a resistor R1 connected in series with the inductor L1 between the input and the capacitor C1. The size of the resistor R1 effectively determines how quickly the capacitor C1 can charge between cycles and may thus determine the maximum repetition rate of the pulse generating circuit. Suitable values of resistance for the resistor R1 may range from about 1 to 100 kΩ, depending on the application and the desired repetition rate. The maximum repetition rate of the pulse generating circuit may e.g. be about 5 MHz or greater.

A differentiator circuit is provided comprising a capacitor C2 and resistor R2 pair that acts to differentiate the trigger pulse of the input signal similarly as in the Kapustinsky circuit shown in Figure 1.

However, a significant improvement in performance relative to the Kapustinsky circuit shown in Figure 1 is provided through the addition of a first diode D1 next to the differentiator circuit C2-R2. The effect of the first diode D1 is illustrated by Figure 3 which shows schematically the evolution of the pulse signal through the circuit of Figure 2.

The top panel of Figure 3 shows the input signal in the form of a positive rectangular pulse. The middle panel of Figure 3 shows the form of the differentiated signal resulting from passing the input signal through the differentiator circuit C2-R2. The differentiator circuit acts in a known way to differentiate the rising and falling edges of the rectangular pulse to respectively provide positive and negative pulses (or “half” pulses).

In the original Kapustinsky circuit shown in Figure 1, both the positive and negative half pulses would then be transmitted to the trigger circuit, which may result in a double pulse feature in the optical output. This problem may be exacerbated when attempting to use the original Kapustinsky circuit to drive relatively faster lower resistance LEDs.

The addition of the first diode D1 as shown in Figure 2 prevents the propagation of the positive half pulse so that only the negative half pulse is transmitted to the trigger circuit. Thus, the addition of the first diode D1 serves to remove the double pulse feature that would be present in the original Kapustinsky output. This represents a significant improvement in performance as the light pulse output generated by the Figure 2 circuit contains a single peak.

It can also be seen from Figure 2 that, unlike in the original Kapustinsky circuit, no inductor is connected in parallel with the diode light source PD1. Instead, a second diode D2 is connected in parallel with the diode light source PD1. It has been found that, especially for lower resistance (faster) LEDs, the use of the inductor is not necessary to generate sufficiently sharp pulses. In particular, the Applicants have recognised that increasing the current passed through the diode light source may help to reduce the length of the generated light pulse, and that because the resistance of the diode light source determines the amount of current that can be passed through the diode light source, the use of lower resistance diode light sources may allow shorter light pulses to be generated. In particular, increasing the current passed through the diode light source may help to reduce the rise time required for the diode light source to reach a desired photon emission rate. Thus, for lower resistance light sources (e.g., of the order around 10 Ω or less), sufficiently sharp pulses may be generated without adding a parallel inductor. This is advantageous because the inductor included in the original Kapustinsky circuit shown in Figure 1 acts to reduce the intensity of the generated light pulse, and this reduction in intensity is avoided by the circuit shown in Figure 2. The second diode D2 is provided generally for current shaping purposes and may help to control the amount of current passed through the diode light source PD1. The second diode D2 may be a fast-switching diode. For instance, faster turn-off of the diode light source PD1 may be achieved by placing a relatively lower capacitance signal diode in parallel with the diode light source PD1. With this configuration, the diode light source PD1 initially conducts, but the signal is then clamped to ground by the second diode D2. In this way, the fall time of the diode light source PD1 may more closely match the rise time, and may provide a sharper pulse.

In preferred embodiments, only the second diode D2 is connected in parallel with the diode light source PD1. This has been found to provide a suitably sharp pulse with sufficient intensity. However, in other embodiments, it is contemplated that an inductor may also be connected in parallel with the second diode D2 and the diode light source PD1. The combination of the inductor and the second diode D2 may help further reduce the pulse width (i.e. relative to the Kapustinsky circuit in Figure 1) but with a corresponding loss in intensity (i.e. relative to the circuit shown in Figure 2).

Figure 4 illustrates the concept of a timing calibration system comprising a plurality of light pulse generator circuits of the types described above, particularly in relation to Figure 2. The driver circuits described herein are relatively compact and robust and it has been recognised that the circuits may thus be installed *in situ* within a detector. This helps reduce the distance that the generated optical pulses have to travel, and thus reduce any dispersion or spreading of the light pulses. By contrast, many existing light pulse generator circuits are unsuitable for *in situ* installation, especially within harsh operating environments such as where a particle detector may typically be located. In existing systems, the light pulse generating circuits are therefore located outside of the detector and the generated light pulses must travel through extensive cabling in order to reach a desired location within the detector, leading to considerable dispersion and broadening of the pulses. The system shown in Figure 4 may be particularly suited for use for timing calibration of large particle physics experiments where there are a large number of detectors all requiring calibration.

As shown in Figure 4, a plurality of light pulse generating circuits 41,42... may be distributed along a common cable 43, and may be operatively controlled using a central control unit 40 that communicates with the individual circuits by sending appropriate signals along the cable 43.

Each of the light pulse generating circuits 41,42... may comprise a feedback mechanism in the form of feedback circuitry that generates a feedback signal indicating when the light pulse generating circuits 41,42 are triggered to generate a light pulse. The feedback signal may then be fed back along the cable 43 to provide this information to the central control unit 40. Because the light pulse generating circuits 41,42... are distributed along the length of the cable 43, there may be an appreciable delay between the central control unit 40 sending a control signal and the respective light pulse generating circuit firing the LED. In order to help accurately calibrate a large number of detectors using the plurality of light pulse generating circuits 41,42... each light pulse generating circuit 41,42...may return a “trigger out” (or feedback) signal co-incident with each generated light pulse, thereby indicating when each of the light pulse generating circuits 41,42...is actually fired.

Figure 5 illustrates in more detail an example of a system of the type shown in Figure 4. As shown in Figure 5, the central control unit 40 comprises a microcontroller 401 for sending data and/or control signals along a first cable 43B to the plurality of distributed light pulse generating circuits 41,42...A second cable 43A is used to supply power to the light pulse generating circuits 41,42...The control signals may thus be passed to a respective microcontroller 411 of the pulse generating circuits 41 in order to generate a trigger signal for generating a light pulse.

The central control unit 40 may individually address each of the plurality of pulse generating circuits 41. For example, each of the microcontrollers 411 of the pulse generating circuits 41 may be arranged to listen for its own pre-programmed address to be broadcast from the central control unit 40, and upon receipt of its respective address, the microcontroller 411 may then be further arranged to wake up and listen for additional set-up parameters including the pulse height, rate and duration, and the start/stop times. The microcontrollers 411 of the individual pulse generating circuits 41 may then generate the required trigger signals for generating the desired light pulses at the desired position along the chain.

To provide the feedback signals described above the trigger signals generated by each of the individual microcontrollers 411 may be returned to the central control unit 40. For example, as shown in Figure 5, the trigger signals may be fed back to the central control unit 40 via a capacitive coupling to the power supply line 43A. In this case, the power supply of the central control unit 40 and the voltage regulator modules may be inductively isolated from the superimposed trigger signal. To compensate for the distance between each of the individual pulse generating circuits 41,42 and the central control unit 40, the trigger signal may be passed through a trigger delay module that delays the light pulse generation. That is, the microcontroller 411 may generate the desired trigger signal and immediately send this back to the central control unit 40. However, the trigger delay module may introduce a pre-determined delay before passing the trigger signal to the LED driver. In this way, the generation of the light pulse is delayed by a certain time so that the light pulse may be generated simultaneously with the feedback trigger out signal returning to the central control unit 40. The trigger delay modules for each of the individual pulse generating circuits 41,42 may thus be programmable to appropriately compensate for the distance between the respective pulse generating circuit and the central control unit 40.

As shown in Figure 5, the central control unit 40 may be connected to a standard power supply (e.g. a variable +8-30 V power supply). The microcontroller 401 of the central control unit 40 may perform voltage regulation. The central control unit 40 may also comprises a connection, such as a USB input 402, for connecting the system to an external processor and/or storage device. The central control unit 40 may also comprise a trigger out line 403 for passing the trigger out feedback signals generated upon firing the light pulse generating circuits 41,42… to the or an external processor and/or storage device.

Thus, in accordance with the embodiments illustrated in Figures 4 and 5, a central control unit 40 is connected to a number of distributed and individually addressable light pulse generating circuits comprising LED driver modules. In principle, any number of light pulse generating circuits may be connected in this way. For instance, it has been found that up to 128 individual light pulse generating circuits may be connected in the manner shown in Figures 4 and 5.

As mentioned above, although embodiments have been described in relation to LED light sources, it will be appreciated that the techniques presented herein also extend equally to other diode light sources including but not limited to laser diodes.

Similarly, although some of the discussion above is presented in the context of a timing calibration system such as for a particle detector system, the techniques presented herein are not limited to this application and may also find utility in a range of other applications requiring faster light pulses including but not limited to time-resolved fluorescence or photoluminescence analyses such as single photon counting techniques, biochemical analysis, detection of fluorescent materials, optoelectronic device testing, Fourier transform infrared spectroscopy, photo-acoustic microscopy, Raman spectroscopy, laser ionisation sources, gating for medical imaging and radiation therapy, flow cytometry and high speed photography.

Accordingly, although the techniques presented herein have been described with reference to particular embodiments, it will be understood by those skilled in the art that various changes in form and detail may be made without departing from the scope of the invention as set forth in the accompanying claims.

Claims:

1. A light pulse generating circuit comprising:

an input for receiving an input signal;

a diode light source;

a charge storage device;

a trigger circuit for triggering a discharge of said charge storage device across said diode light source to generate a light pulse; and

a differentiator circuit for differentiating said input signal to produce a differentiated signal, wherein the differentiated signal is provided as an input to said trigger circuit to trigger said discharge,

wherein a first diode is arranged relative to the differentiator circuit so that when a pulse input signal is provided to the input such that the differentiator circuit differentiates the pulse input signal to produce a differentiated signal comprising a positive pulse and a negative pulse, the first diode substantially prevents the propagation of one of said positive pulse and said negative pulse so that only the other of said positive pulse and said negative pulse is provided as an input to said trigger circuit to trigger the discharge so that a light pulse having a single peak is generated.

2. The circuit of claim 1, wherein the polarity of said input signal is positive, and wherein the circuit is arranged such that said light pulse is generated in response to a positive input signal being provided to the circuit.

3. The circuit of claim 1 or 2, comprising a second diode arranged in parallel with said diode light source, wherein said second diode is connected in the same direction as the diode light source.

4. The circuit of any of claims 1, 2 or 3, wherein no inductor is connected in parallel with said diode light source.

5. The circuit of any preceding claim, wherein said input signal comprises a power input signal component that is used to charge said charge storage device and a trigger input signal component that is passed to the differentiator circuit and used to

trigger the generation of said light pulse, said trigger component and said power component being received at a common input.

6. The circuit of claim 5, comprising an inductor arranged to decouple or split the power component of said input signal from the trigger component.

7. The circuit of any preceding claim, wherein said diode light source has a resistance of less than about 20 Ω.

8. The circuit of any preceding claim, wherein said charge storage device comprises one or more capacitors.

9. The circuit of any preceding claim, wherein said trigger circuit comprises a pair of transistors, preferably arranged as a complementary transistor pair regenerative switch.

10. The circuit of any preceding claim, wherein said differentiator circuit is a passive differentiator circuit comprising a capacitor-resistor pair.

11. The circuit of any preceding claim, wherein said input comprises a USB or Ethernet connection for connecting said circuit to one or more processors and/or power supplies.

12. A light pulse generator system comprising a light pulse generating circuit as claimed in any preceding claim and one or more processors and/or power supplies for providing said input signal.

13. A light pulse generator system comprising a plurality of light pulse generating circuits as claimed in any of claims 1 to 11, wherein the plurality of light pulse generating circuits are distributed along a cable, and a central control unit, wherein said central control unit is connected to said cable and arranged to transmit control signals along said cable for addressing each of said plurality of light pulse generating circuits.

14. The system of claim 13, wherein each of said plurality of light pulse generating circuits comprises feedback circuitry arranged to send a feedback signal

along said cable to said central control unit indicating the triggering of said light pulse generating circuit.

15. The system of claim 14, wherein each of said plurality of light pulse generating circuits further comprises a delay module, wherein said delay module acts to delay the generation of light pulses at said light pulse generating circuit, wherein the delay modules for each of said plurality of light pulse generating circuits are configured or programmable to introduce a delay that substantially matches the time taken for said feedback signal to reach said central control unit from each of the respective plurality of light pulse generating circuits.

16. A method of using the system of claim 13, 14 or 15, comprising:

installing each of said plurality of light pulse generating circuits at a respective position where it is desired to generate a light pulse; and

transmitting along said cable a control signal from said central control unit to one or more of said plurality of light pulse generating circuits in order to generate a light pulse at the respective positions of the one or more light pulse generating circuits.

17. A method of using a light pulse generating circuit as claimed in any of claims 1 to 11 or a system as claimed in any of claims 12 to 16 comprising:

providing an input signal to said light pulse generating circuit(s); and

using said light pulse generating circuit(s) to generate a light pulse.

18. The method of claim 17, wherein said input signal comprises a pulse, optionally wherein said input signal comprises a positive rectangular pulse.

19. The method of claim 17 or 18, comprising providing a positive power signal to said light pulse generating circuit(s) for charging said charge storage device(s), optionally wherein said input signal is superimposed on said positive power signal.

Fig. 1

Prior art

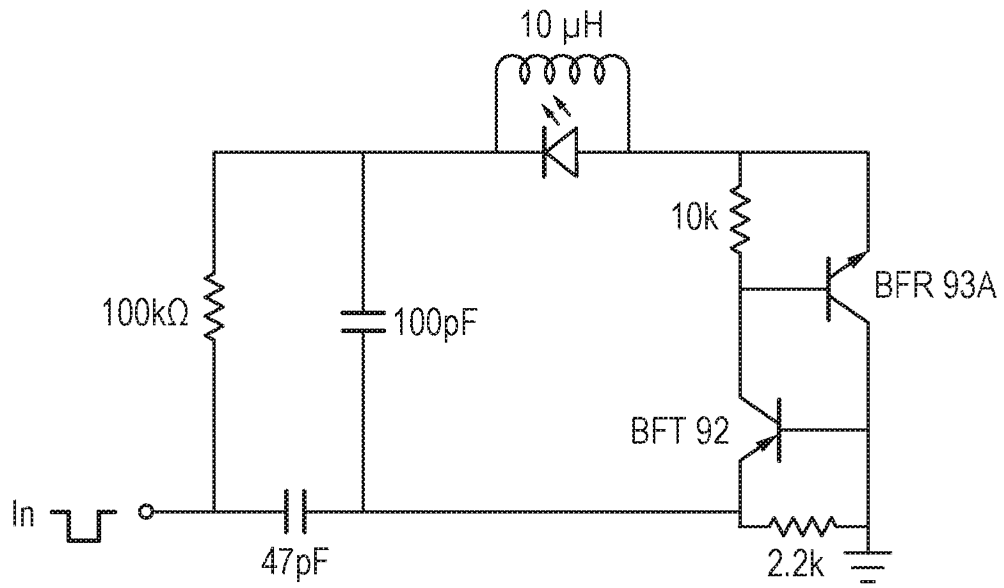


Fig. 2

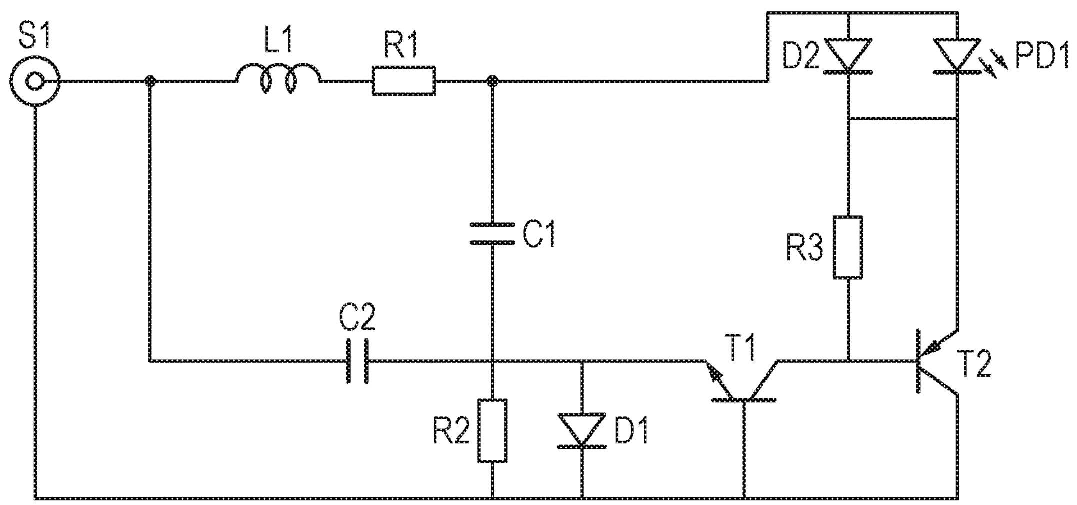


Fig. 3

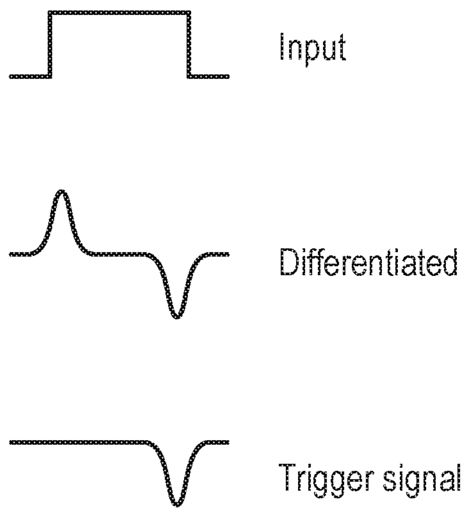


Fig. 4

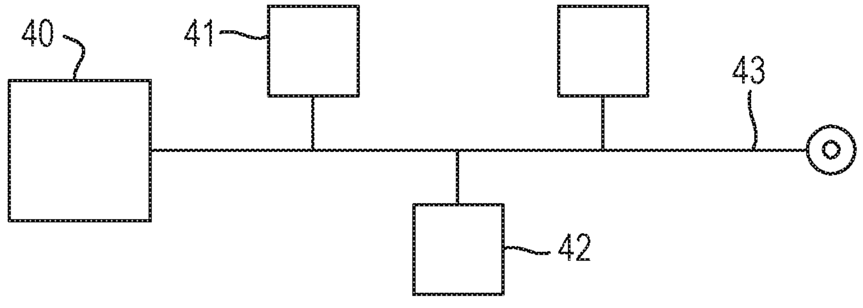
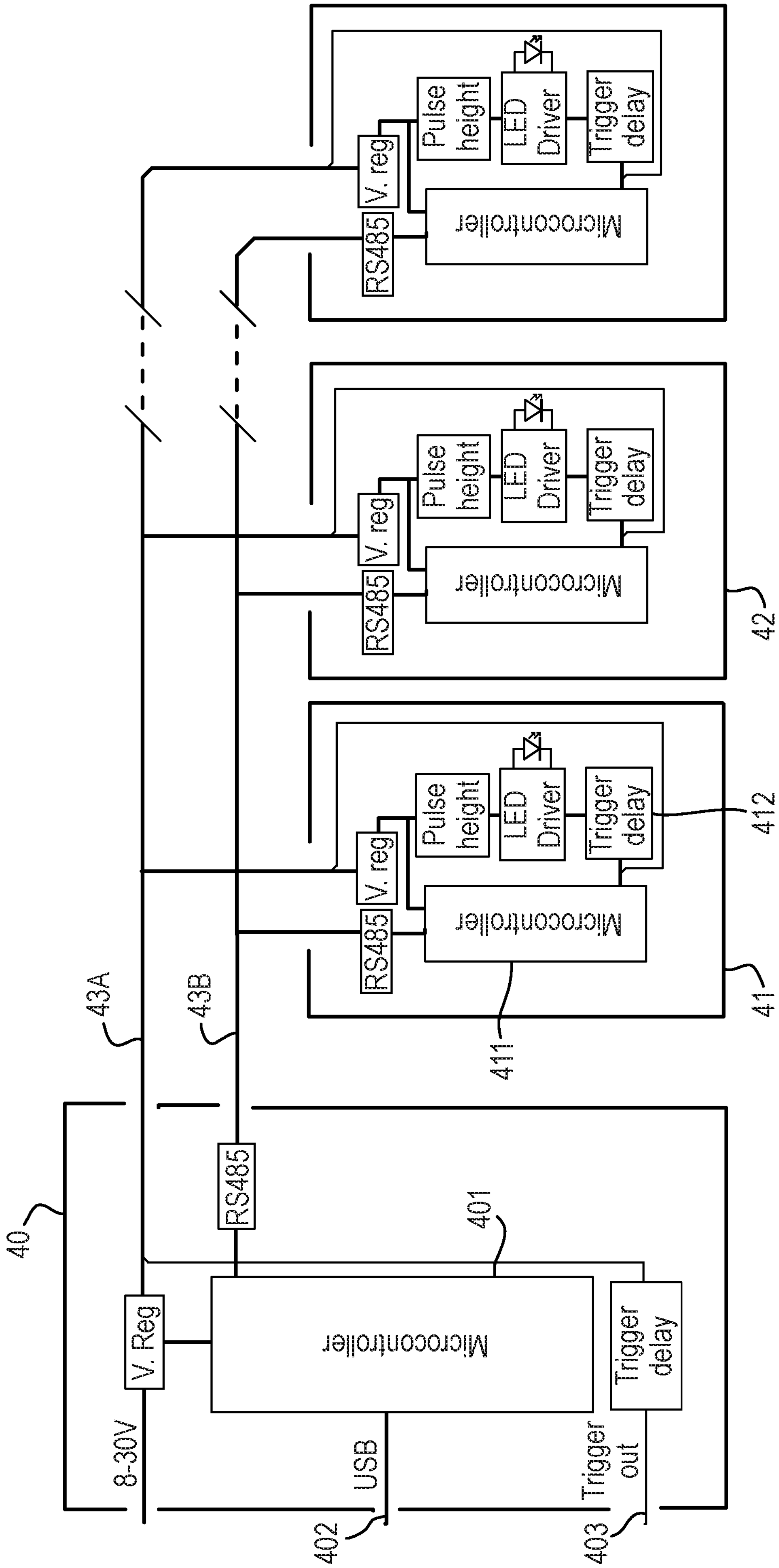


Fig. 5


40
401
402
403
8-30V
USB
Trigger out
V. Reg
Microcontroller
Trigger delay
RS485
43A
43B
41
411
412
42
RS485
V. reg
Microcontroller
Pulse height
LED Driver
Trigger delay

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2018/051308

A. CLASSIFICATION OF SUBJECT MATTER
INV. H05B33/08 H03K3/57
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
H05B H03K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 3 898 588 A (SKAGERLUND LARS-ERIK) 5 August 1975 (1975-08-05)	1-4, 7-12, 17-19
A	the whole document	5,6, 13-16

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 July 2018	01/08/2018

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Waters, Duncan

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/GB2018/051308

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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